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A NEW APPROACH TO LOW-COST OPEN-TYPED SUBSONIC COMPRESSIBLE FLOW WIND TUNNEL FOR ACADEMIC PURPOSE

ABDULRAHMAN A. ALROBAIAN[1], S. A. KHAN[2], MOHAMMED ASADULLAH[2], FHARRUKH AHMED. G. M[3] & IMTIYAZ. A[3]

[1]*Assistant Professor, Qassim University, Buraidah, Saudi Arabia*

[2]*Department of Mechanical Engineering, International Islamic University Malaysia*

[3]*Department of Mechanical Engineering, Bearys Institute of Technology, Mangalore, Karnataka, India*

ABSTRACT

The most challenging task concerning wind tunnel description is, to ascertain the supporting mechanism at high-speed flows inside test section with least complexity and low-cost. This paper presents the design and development of a simple and cost effective test section for a subsonic compressible wind tunnel for educational purpose. The objective of this open-type wind tunnel was to demonstrate flow around model without any interference at high-speeds. In this work, that is study of flow analysis, a subsonic square nozzle was fabricated to achieve maximum velocity of 340 m/s. The test section is 25 mm x 25 mm x 70 mm and is externally attached with travers. It starts from length 25 mm to avoid dead zone and ends at 95 mm to avoid end effects, and on one of the surfaces pressure taps were provided for measuring pressure at different locations inside the wall of duct. The duct length was taken as 100 mm and the pressure taps were at the distance of 8 mm, 16 mm, 24 mm, 49 mm, 59 mm, 80 mm and 90 mm to measure wall pressure. They were connected to sensors through PVC tubes and further to DAQ using LabVIEW interface, and finally to the computer. In addition to this, the flow through the duct can be visualized using transparent glass to find the reattachment point for our recirculation bubble. A new concept of attaching models in a 3 D travers was found very easy for inserting it from behind in test section, and thereby interference and breaking of strings was eliminated. Calibration was done through pitot tube at the exit of test section in y and z direction. The nature of graph tells about the correctness of the designed wind tunnel test section. After calibration, we found that the exit velocity is constant for approximately 80 percent area. This area is the effective test section work area.

KEYWORDS: Subsonic Compressible Flow, Mach Number, Wind Tunnel, Base Pressure & Wall Pressure

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Original Article

INTRODUCTION

The high-speed dynamics has developed vehicles in land, sea and air, but the cost have been very high due to unavailability of academic low-cost wind tunnel for these speeds in educational institutes. The dynamic and kinematic parameters of fluid flow around an object can be tested in wind tunnel using dimensional analysis. Wind-tunnel testing technique is vastly employed for full as well as model scale components [1]. Also, maintenance cost for most of the high-speed wind tunnels is very high in research centre such as in NASA Aeronautics Test Program [1]. They are often classified based on flow regimes such as Reynolds number and Mach number or are classified based on its size of test section or are classified based on its application [2].

Classification of wind tunnel are of many types such as subsonic incompressible flow wind tunnel [3], subsonic compressible flow wind tunnel [4], supersonic wind tunnel [5] and hypersonic wind tunnel [6]. Wind tunnels are also classified as closed [7] and open loop [8] but are mostly for low-speed incompressible flows. Measurement and control aspect of wind tunnel was studied by [9] but compressible flow was not touched at all. Wind tunnel testing methodology was applied to 200 airfoils, but at a very low speed [10]. Cost affective wind tunnel were investigated by [11] but for incompressible flow only. Development of low-cost wind tunnel for educational purpose was done [12] but for a very low speeds. Another wind tunnel for educational purpose flow visualization and separation of boundary layer was investigated [13] but compressibility was not touched. Study of low intensity turbulent level was done by achieving velocity up to 90 m/s [14] but is far from transonic flows. A wind tunnel was designed and developed to achieve speed of 48 m/s [15] but was confined to incompressible flows only. A CFD approach was developed for simulating the flow condition in closed-circuit low speed wind tunnel [16]. So, it’s very clear from literature that a lot of wind tunnel for incompressible flow wind tunnel for educational purpose have been evaluated but very few studies for high-speed subsonic compressible flow has been investigated. Thus, the need for low-cost compressible flow wind tunnel for educational purpose needs to be addressed. A new approach for facilitating experiments in test section has been studied and illustrated in Figure 1.

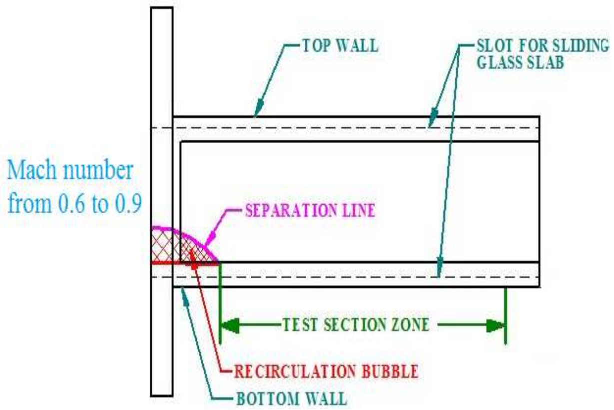

Figure 1: Test Section of Wind Tunnel

Principle parts of a wind tunnel are driving system, storage tank, settling chamber, parallel wire mesh, operating fluid circuit, contracting nozzle, test section, square duct test section and Data Acquisition System.

DESIGN METHODOLOGY

Wind-tunnel design should be simple and cost effective. It should be not limited to great research centers like NASA and ISRO, but also be available in small organizations and research centers to facilitate academicians and researchers in general.

Driving System

This system determines how the fluid is compressed by a motor of 20 HP and stored in storage tank at pressure of approximately 200 psi.

Figure 2: Compressor Unit (20HP)

This electric powered screw air compressor of capacity 55cfm of air at a pressure of nearly 138 psi by a cage induction motor is used to compress air as shown in Figure 2, and stored in the pressure vessel.

Storage Tank

Figure 3: Storage Tank

Two storage tanks (pressure vessel) made of mild steel and having pressure value of about 200 psi and capacity of 2 $m^3$is shown in Figure 3. Safety valve is available on the top so as not to exceed the limits.

Settling Chamber

A settling chamber is provided with provision at the centre for model mounting as shown in Figure 4. The flow from the fan is settled in this large settling chamber. The settling chamber directs the airflow. Uneven turbulent flows can cause unpredictable forces to be experienced and measured in the test section.

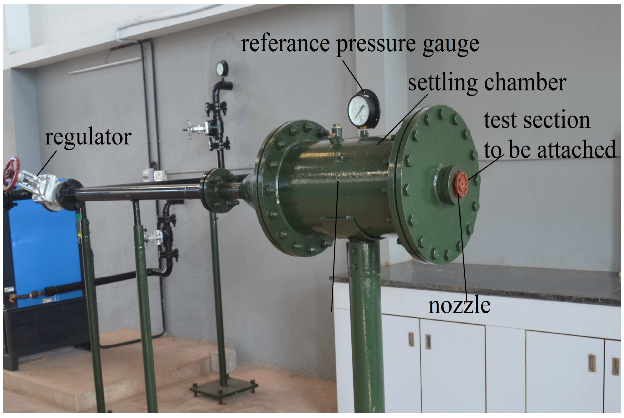

Figure 4: Experimental Setup

The less turbulence there is, the better the wind tunnel will simulate actual flowing conditions. The settling chamber usually includes, a parallel wire mesh smoothing screens that produces a smooth airflow

Parallel Wire Mesh

Figure 5 shows one layer of wire mesh. It breaks up unsteady flow in to a steady flow and reduces large scale oscillations in to small scale and reduces boundary layer growth. Parallel screens placed in the settling chamber with required porosity, provides lower value of turbulence [17].

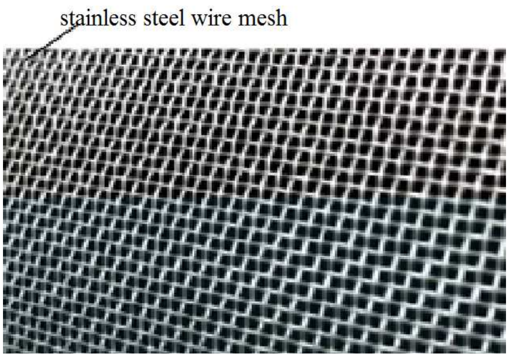

Figure 5: Wire Mesh inside Setting Chamber

Thus, make screens necessary to decay fluctuations, before passing through the contraction.

Operating Fluid Circuit

Operating fluids in wind tunnel are closed-type in which, air circulates in a loop circuit through a fixed mass of fluid without leakage or open- type, in which air enters from one side and exits to the atmosphere from the other through the test section. We will focus on open-type subsonic high-speed compressible flow regime.

Contracting Nozzle

The convergent nozzle was designed in solid edge and then fabricated from brass as shown in Figure 6. The nozzle used is a square nozzle with a maximum speed of 340 m/s. The flow quality in test section duct is dependent on the convergent nozzle angle. In our case, the angle is 15^0.

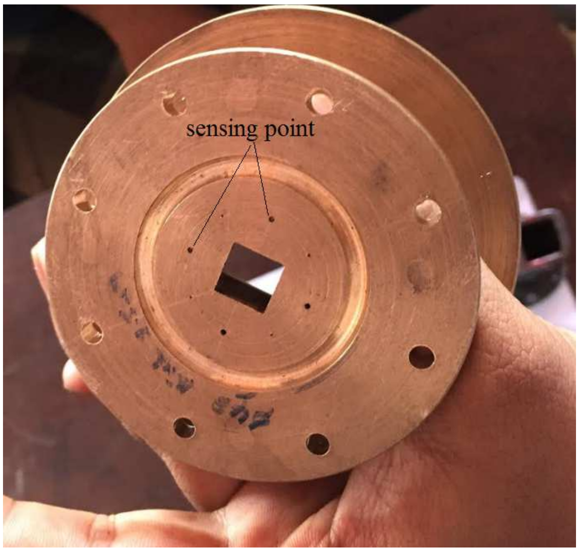

Figure 6: Subsonic Convergent Nozzle

Square Duct Test Section

The square test section is one of the most significant parts in wind tunnel and is shown in Figure 7.

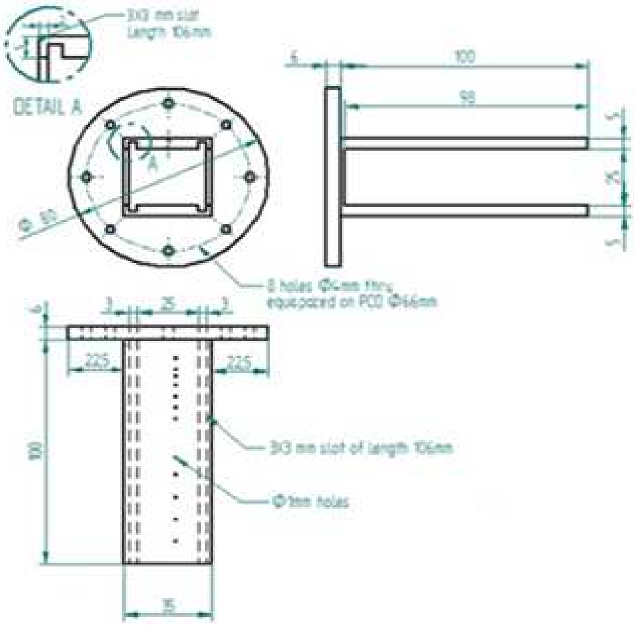

Figure 7: Design and Fabrication of Wind Tunnel Test Section

It allows us to measure and observe flow field around the model. The wind tunnel design starts with selecting and fabricating the test section, keeping in mind the accessibility and installation of wind tunnel test model and instrumentation. The test section should be long enough, so that disturbances behind the base are damped or avoided before reaching the test section. Also, care should be taken not to keep it too long that so as not to invite boundary layer separation leading to loss of energy. The test will be carried out for flow speeds less than 340 m/s (M=1). The tests carried are at Mach from 0.6 to 0.9. Some of important specifications are shown in table below.

Table 1: Specification of Wind Tunnel Test Section

S. No	Design Feature Outcomes	
1	Cross-sectional Shape	Square
2	Material	Brass
3	Side Wall	Transparent Glass
4	Length of Test Section	70 mm
5	Height of Test Section	25 mm
6	Width of Test Section	25 mm
7	Inlet Area	625 mm^2
8	Outlet Area	625 mm^2
9	Wall Thickness	2 mm
10	Semi Convergent Angle	15 ^{o}
11	Length of Convergent Part	37.5 mm

Data Acquisition System (DAS) Software

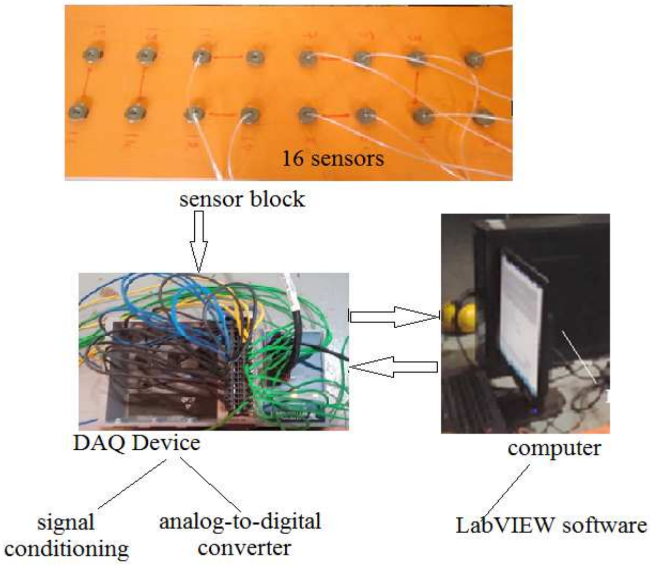

Figure 8: Data Acquisition System

Data acquisition system consist of sensors, DAQ measurement hardware and a computer with a programmable measuring of a physical phenomenon such as pressure in the form of voltage through DAQ and converting it to digital signal and then forwarding it to computer with programmable software, such as Lab VIEW. DAQ device acts as an intermediate between wind tunnel test section measuring point for pressure ports and computer.

EXPERIMENTAL SETUP AND MODEL DESIGN

Figure 9 shows experimental setup used for present study. At the exit periphery of the nozzle, there are four holes for measuring base pressure (P_b). Test section pressure taps were provided on the duct to measure wall pressure distribution. First five holes were made at an interval of 5 mm each and remaining was made at an interval 10 mm and 20 mm each.

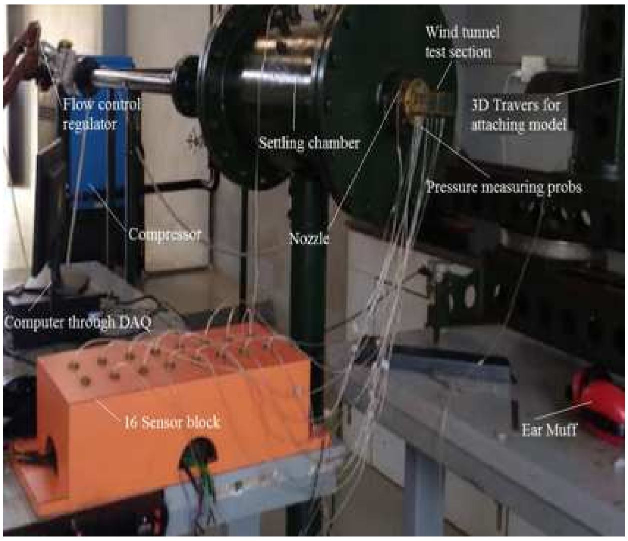

Figure 9: Experimental Setup of Suddenly Expanded Nozzle

The test section and nozzle is designed by using solid edge as design tool.

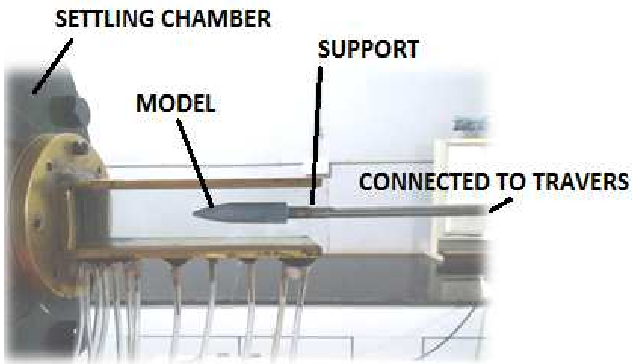

Figure 10: Wind Tunnel Test Section

The Nozzle used in experiment is of square cross section, which can attain Mach=1. All the ducts are designed with same width and height which is 25×25 mm^2 and the lengths of ducts is 4W. A dummy model inside the wind tunnel test section is shown in Figure 10.

Figure 11 sows three-dimensional travers. It is used for easy installation of model in test section and calibration of wind tunnel test section at exit. Travers mechanism has 6 degree of freedom, three translational and three rotational.

Figure 11: Travers as a 3D Supporting Mechanism

Travers can also be used in holding pitot tube in different positions to measure exit pressure, as shown in Figure 12.

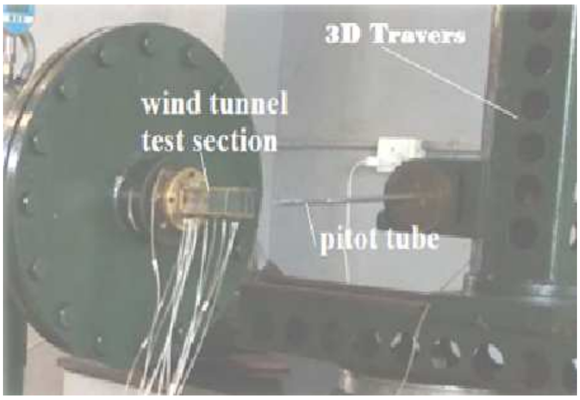

Figure 12: Pitot Tube with Travers as a Measuring Device

RESULTS AND DISCUSSIONS

Calibration of Wind Tunnel Test Section at Exit

The fabricated nozzle with test section duct was calibrated at the exit. This is mandatory to check the steadiness and losses. The nozzle was calibrated by measuring the total pressure along a diameter using a pitot tube as shown in Figure 12. Calibration shows the uniform Mach number near the centre at the duct exit cross-section and decreases near the wall due to end effects. The Mach number profile is shown in Figure 13 and Figure 14.

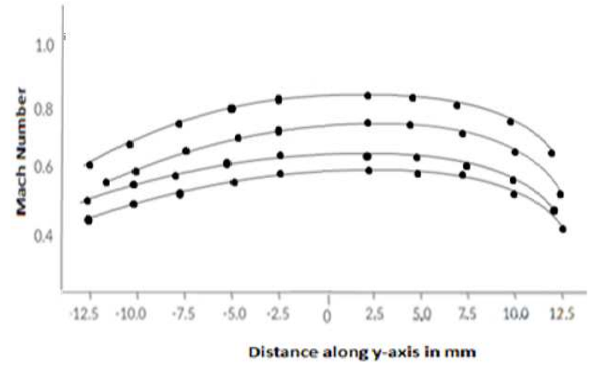

Figure 13: Mach Number Variation in y Direction

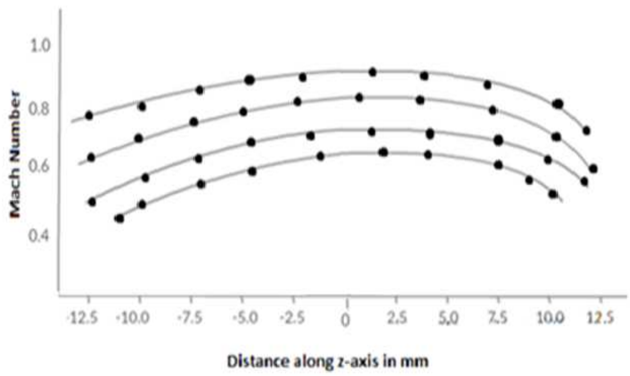

Figure 14: Mach Number Variation in z Direction

Overall the trend in both the cases shows a steady flow at approximately 80 percent of area, both in y and z direction.

Base Pressure Results

Base recirculation zone is full of depression and loss of energy. We need to know its trend, to avoid it for our wind tunnel test section. When the flow separates, it has the tendency to reattach.

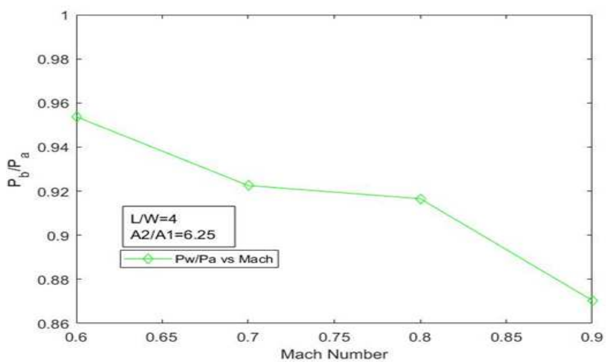

Figure 15: Base Pressure Variation with Mach Number

Figure 15 shows decrease in base pressure with increase in Mach number. That means base drag is increases. As we can see from the trend that at higher Mach numbers base pressure is very high as compare to the lower Mach number. So, base drag will be very high at higher Mach numbers. This trend was also observed by several researchers in experimentally investigating on base flows while manipulating base pressure by dimples [18], aerospike [19], cylinder [20]

etc. and numerically simulated through CFD analysis by [21].

Wall Pressure Results

Wall pressure results not only give the reattachment point, but also give us the overall behavior of flow field in the test section. This reattachment point is approximately 20 to 30 percent for compressible subsonic flows. We, through our experimentation found it approximately 25% as shown in Figure 16. Given below are wall pressure results:

For Mach = 0.6 we can observe sudden rize at X/L = 0.2, and then reverses back close to inetial position at X/L = 0.25 and slowly to a steady state with very less fluctuation. Further, Mach = 0.7 gives a slight rize at X/L = 0.22 and then falls deep at X/L = 0.25, there after regains steadiness. For Mach 0.8 and 0.9 too the rize and fall can be seen upto X/L = 0.25, there after trend goes towards steadiness. The highest Mach number showed the lowest wall pressure during fall, and the lowest Mach number showed the highest wall pressure during fall. Clearly we can see from Figure 16, that there was fall of wall pressure for all Mach numbers at 0.25, but there after it nearly regains the pressure and becomes stable. This fall was the end of recirculation zone near stagnetion point. At, X/L = 0.25 we could see a dip for all the points giving $P_w/P_a = 0.92$, there after the presure increses to the initial presure. For that reason, our high speed wind tunnel test section starts from 45 mm and ends at 95 mm to avoid end effects. This might vary for different ducts and for different regimes, but in most of the cases for microjets the trend was quite similar [22].

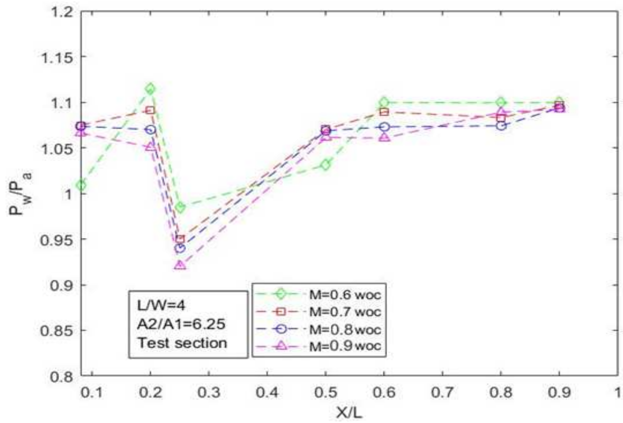

Figure 16: Wall Pressure Distribution for Wind Tunnel

CONCLUSIONS

The design and fabrication of test section, for an open-type subsonic compressible flow high-speed wind tunnel of Mach numbers as 0.6, 0.7, 0.8 and 0.9 were presented. Flow field around the model was measured as base pressure and wall pressure readings. The following conclusions have been drawn after this investigation:

- For Mach number 0.6, the wind tunnel test section L/W= 4 gives good performance and has the advantage of having shorter length and is quite stable after 45% of length.
- For Mach number 0.7, the wind tunnel test section is quite stable and after 45 % starts getting stable
- For Mach number 0.8, and 0.9, the wind tunnel test section is quite stable between 0.45 and 0.5.
- Thus, from 45 mm to 95 mm out wind tunnel test section is designed

- One of the most interesting results we got is that, flow field is stable inside wind tunnel test after 50 % of length wise distance.
- Visualization to find reattachment point is possible through transparent side walls
- Pressure plots give idea about flow field around the model
- Calibration in Y and Z direction showed nearly constant line for different Mach number at the exit of duct.

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